Measurement of the $|V_{cb}|$ element of the CKM matrix in $t\bar{t}$ decays with the ATLAS detector

YSF talk at Moriond EW

La Thuile, 21st of March 2026

Adam Warnerbring, on behalf of the ATLAS collaboration

arXiv: 2603.16414

Public webpage: TOPQ-2019-14

Universität Siegen

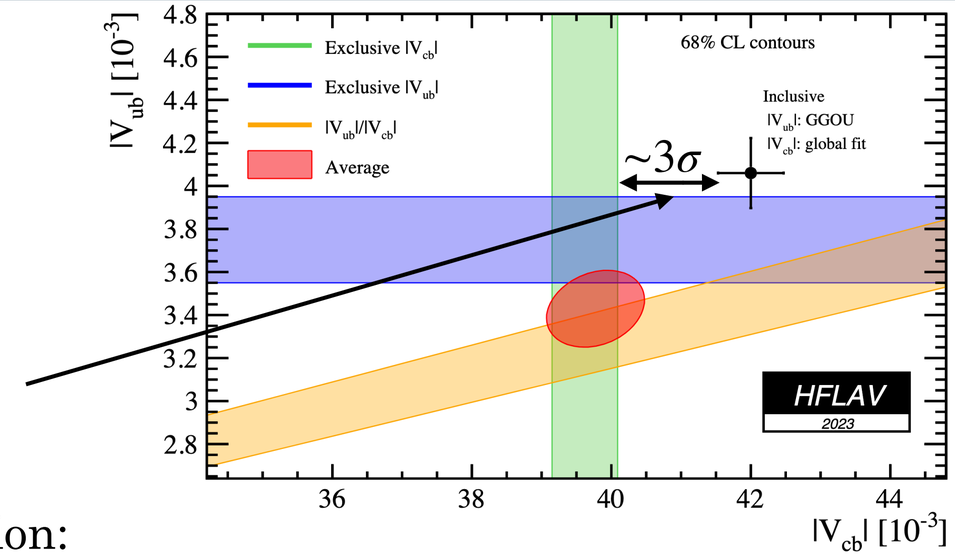
HEP Experimental High Energy Physics
CPPS Center for Particle Physics Siegen

Motivation for a $|V_{cb}|$ measurement in events with on-shell W-bosons

- All $|V_{cb}|$ measurements so far are in B-hadron decays, most precise determinations from inclusive and exclusive decays:

$$|V_{cb}|_{\text{world avg.}} = (41.1 \pm 1.2) \times 10^{-3}$$

- Long standing tension between inclusive and exclusive measurements



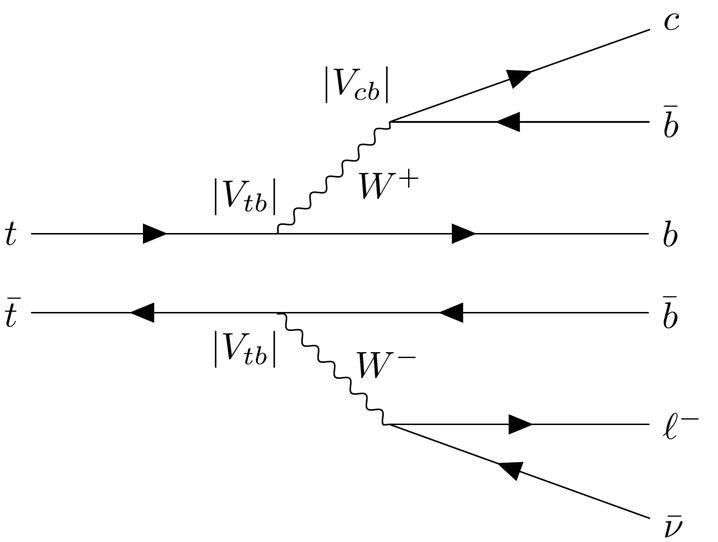
Physical Review D 113, 012008 (2026)

- In this analysis, $|V_{cb}|$ is extracted through the $W \to cb$ branching fraction:

$$|V_{cb}|^2 = \frac{\mathcal{B}(W \to cb)}{\mathcal{B}(W \to cq)} = \frac{\mathcal{B}(t\bar{t} \to b\,cb, b\,\ell\nu)}{\mathcal{B}(t\bar{t} \to b\,cq, b\,\ell\nu)}$$

- First measurement of $|V_{cb}|$ in on-shell W-boson decays

- Measurement complementary to previous $|V_{cb}|$ determinations, but challenging due to the small expected $W \to cb$ branching fraction: $\mathcal{B}(W \to cb) \approx \frac{1}{1800}$

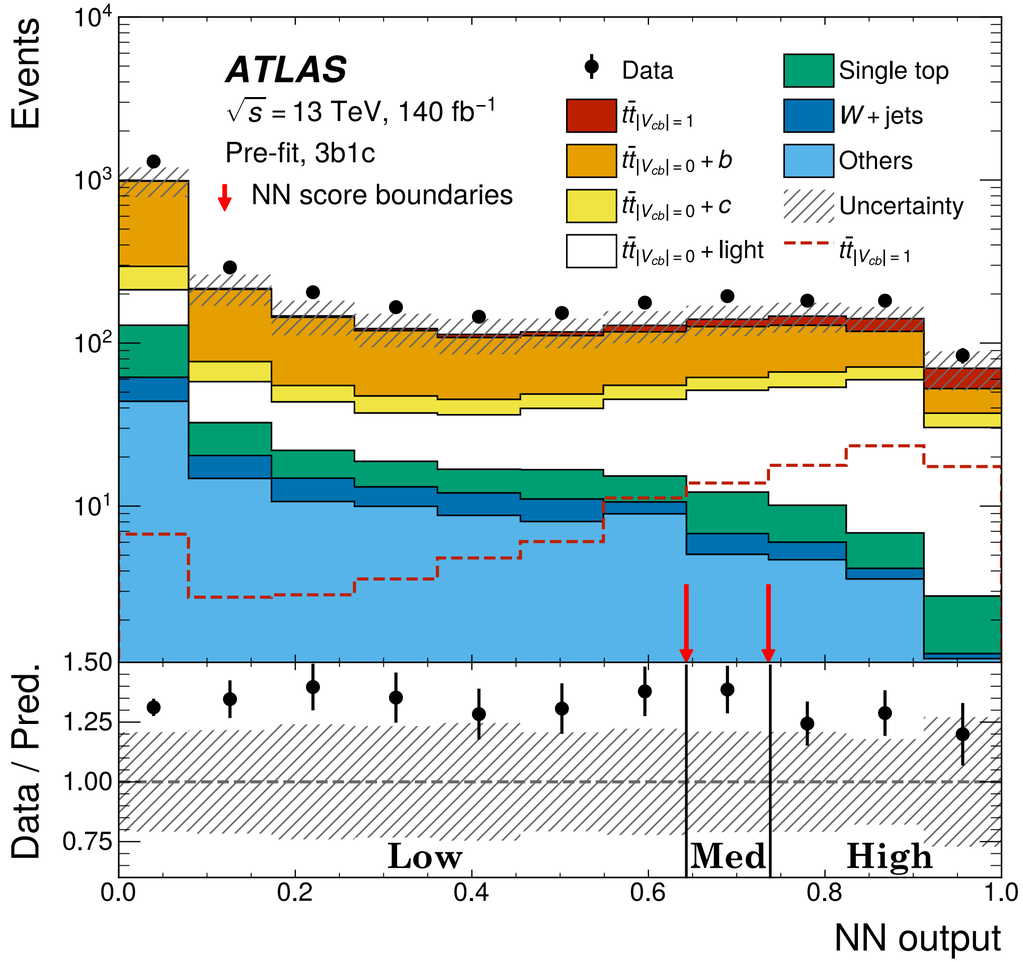


Overview of the analysis strategy

- MC $t\bar{t}$ events split into $t\bar{t}_{|Vcb|=1}$ if $W \rightarrow cb$, otherwise $t\bar{t}_{|Vcb|=0}$
- Event selection: Single electron or muon and exactly 4 jets
- Fit regions defined by the number of b- and c-tagged* jets: (1b1c, 1b2c, 1b3c, 2b0c, 2b1c, 2b2c, 3b0c, 3b1c)

Neural network (NN) classifier:

- Trained to classify events with all 4 jets from the $t\bar{t}$ system
- Used to separate $t\bar{t}$+HF and other backgrounds from $W \rightarrow cb$ events
- 3 NN bins (Low, Med, High) used in the fit

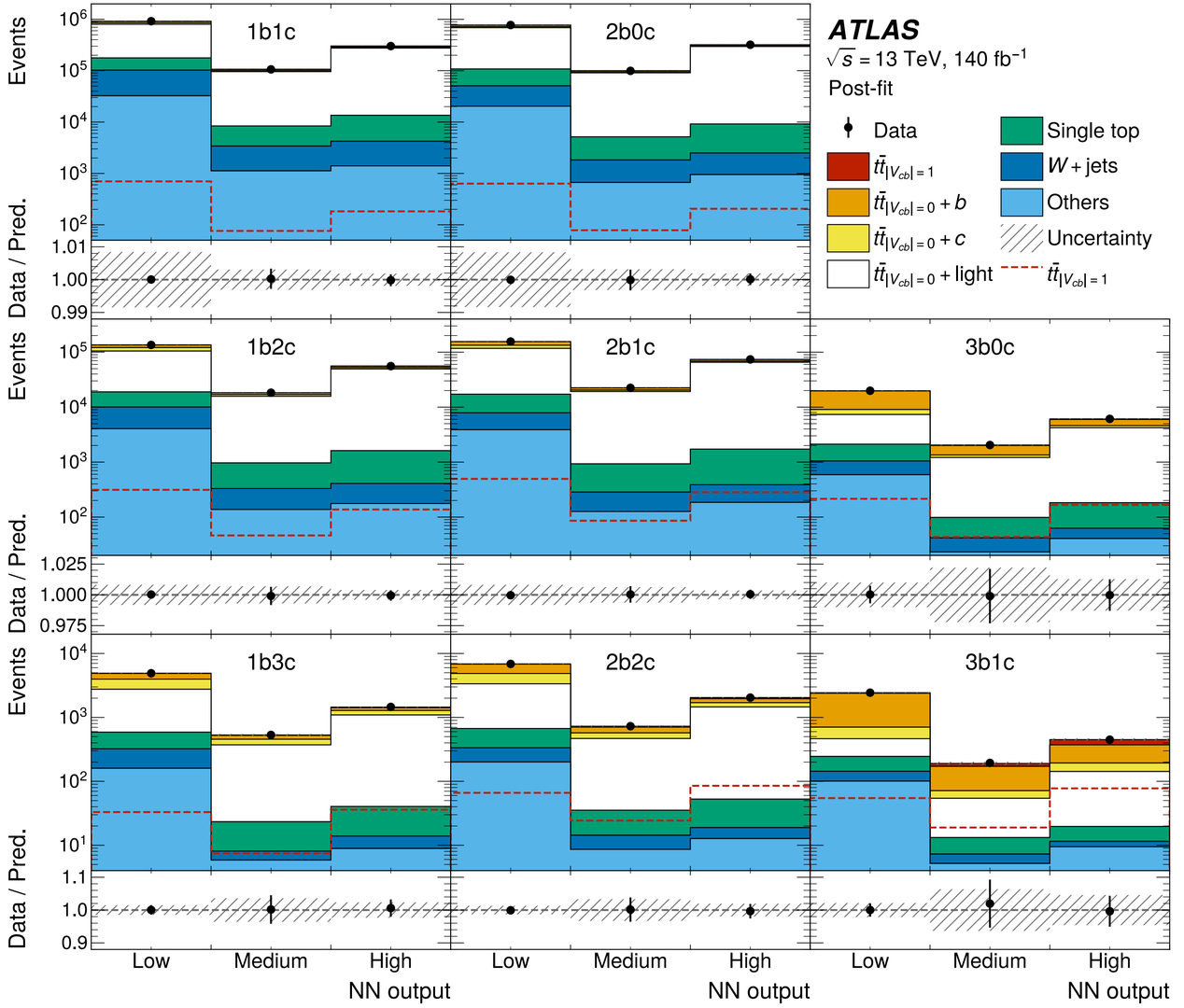


Pre-fit NN distribution in the region with 3 b-tagged and 1 c-tagged jet

*b-jet: Tagged by DL1r at the 0%-60% b-efficiency working point
c-jet: Tagged by DL1r at the 60%-85% b-efficiency working point

Overview of the analysis strategy

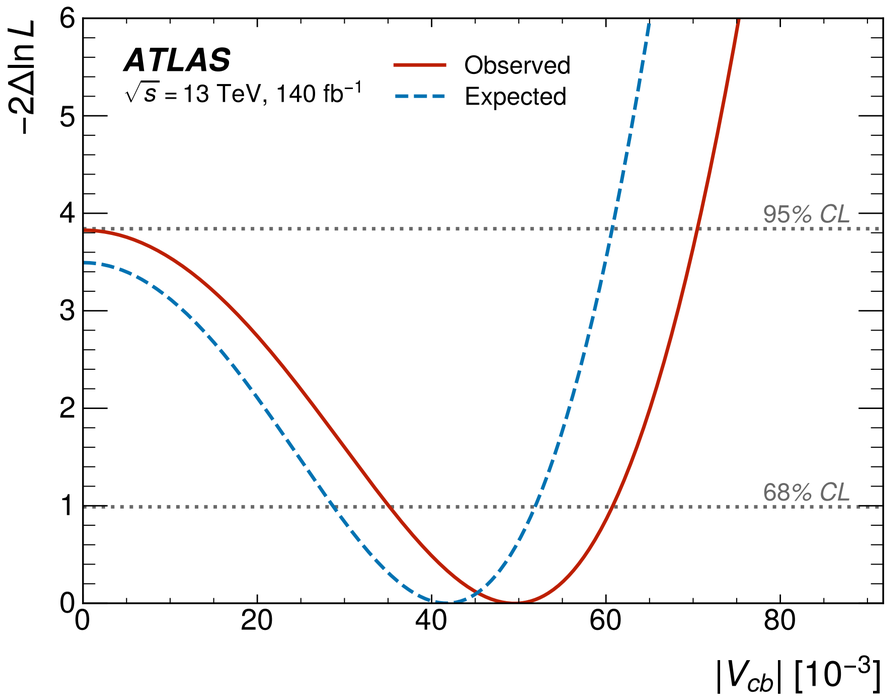
- $|V_{cb}|$ extracted from the $t\bar{t}_{|Vcb|=1}$ normalisation in a binned profile likelihood fit
- Normalisation of $t\bar{t}_{|Vcb|=0}$, $t\bar{t}+b$ and $t\bar{t}+c$ measured simultaneously
- Can not use central ATLAS c-jet calibration since it assumes a fixed $|V_{cb}| \implies c$-jet efficiency and mis-tag rates calibrated in-situ
- Regions with many $t\bar{t}_{|Vcb|=0}$ events used to constrain charm jet efficiency ε_c and $c \to b$ mis-tag rate f_{cb}



Post-fit yield in all bins used in the fit

Results

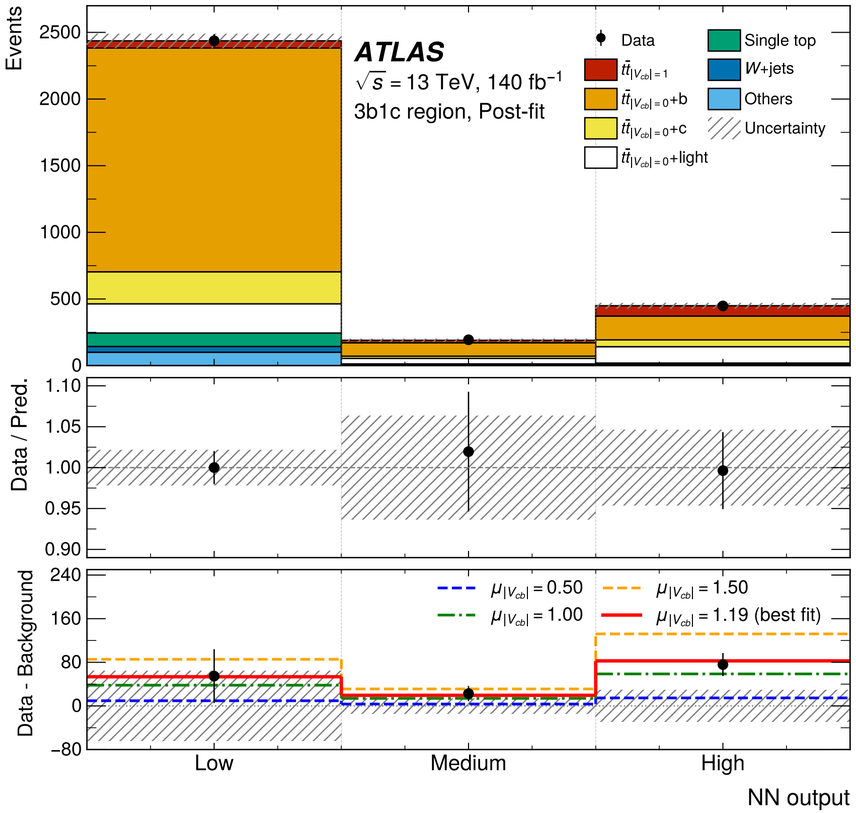
Best fit $|V_{cb}|$ value: $|V_{cb}| = \left(50^{+11}_{-14}\right) \times 10^{-3} = \left(50^{+7}_{-9}\ (\text{stat.})\ ^{+9}_{-10}\ (\text{syst.})\right) \times 10^{-3}$



Negative log likelihood scan of $|V_{cb}|$

Uncertainty	Up/Down [10^{-3}]
Modelling of $t\bar{t}$	8/9
↪ PS and hadronisation	5/6
↪ Others	5/6
Jet flavour tagging calibration	2.9/3.1
↪ Light-jet	2.5/2.8
↪ b-jet	1.2/1.3
Simulation statistical uncertainty	2.6/2.7
Jet calibration	2.4
Modelling of non-$t\bar{t}$ processes	1.6
Others	0.8
Systematic uncertainty	9/10
Statistical uncertainty	7/9
Total uncertainty	11/14

Uncertainty breakdown in $|V_{cb}|$



Post-fit yields in the 3b1c region

Summary

2603.16414

- Presented the first measurement of $|V_{cb}|$ in $t\bar{t}$ events performed at ATLAS

- The measured value is:

$$|V_{cb}| = \left(50^{+11}_{-14}\right) \times 10^{-3} = \left(50^{+7}_{-9}\ (\text{stat.})\ ^{+9}_{-10}\ (\text{syst.})\right) \times 10^{-3},$$

  compatible with the current world average: $|V_{cb}|_{\text{world avg.}} = (41.1 \pm 1.2) \times 10^{-3}$

- The systematic and statistical uncertainty are of similar size, with $t\bar{t}$ modelling being the main contribution to the systematic uncertainty

- First measurement of $|V_{cb}|$ involving on-shell W bosons and is probing the weak scale, but the uncertainty is not yet competitive with B-factory results.

Backup slides

Event selection

Event selection:

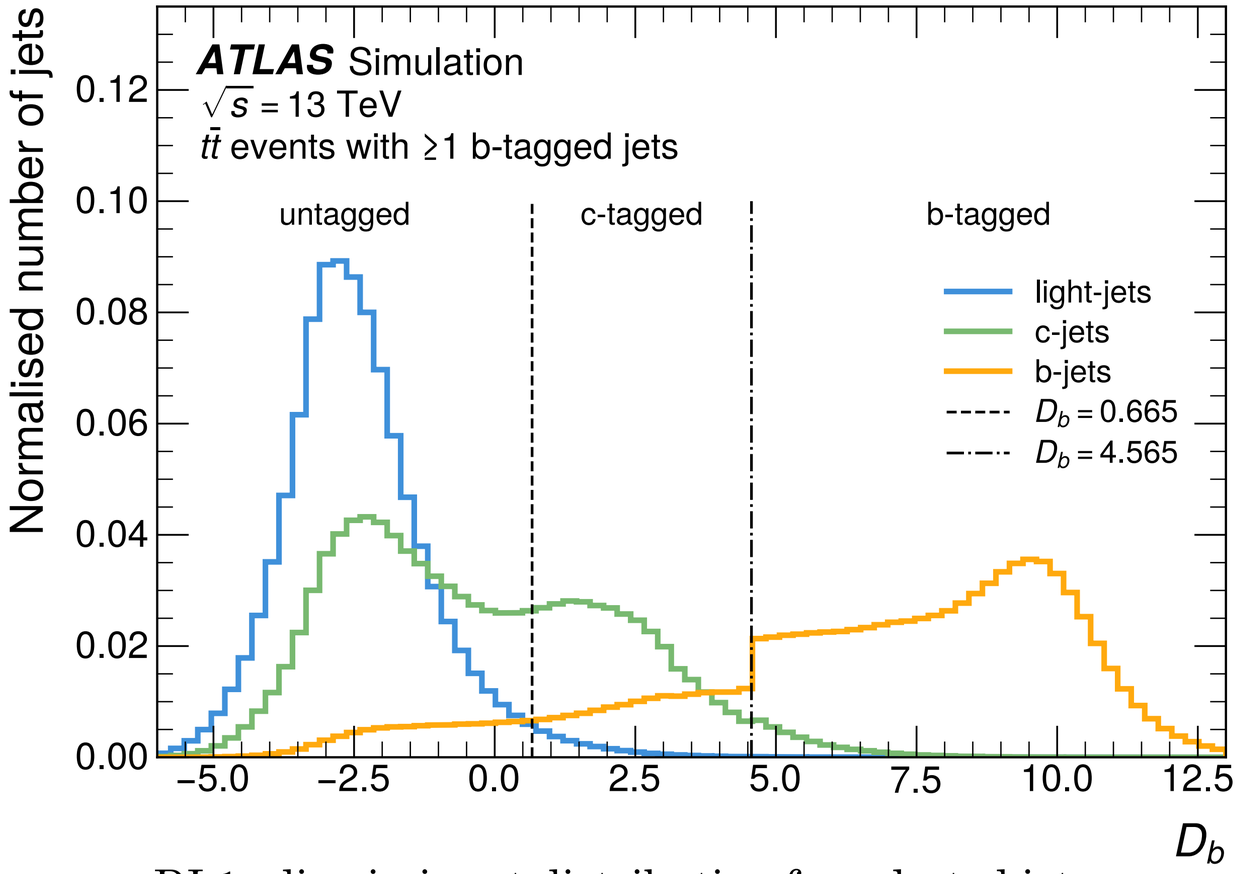
- Trigger on and select electron or muon above 27 GeV† and with $|\eta| < 2.5$
- Exactly 4 jets above 25 GeV and with $|\eta| < 2.5$
- At least 1 b-tagged and 2 b- or c-tagged jets, using DL1r at the 0%-60% and 60%-85% b-efficiency working points

Flavour tagging working points

b-tagged jet: Tagged by DL1r at the 0%-60% b-efficiency working point

c-tagged jet: Tagged by DL1r at the 60%-85% b-efficiency working point

The plot shows the corresponding cuts on the DL1r b-tagging output score



DL1r discriminant distribution for selected jets (each jet class normalised)

Results and uncertainty breakdown

- $t\bar{t}$+HF normalisations larger than predicted in MC, but agree with previous ATLAS measurements (Phys. Lett. B 860 (2025) 139177)

- Charm tagging rates consistent between NN bins, agree with central ATLAS calibrations (Eur. Phys. J. C 82 (2022) 95)

Parameter	Value	Parameter	Value		
			Low	Med	High
$\mu_{V_{cb}}$	$1.19^{+0.27}_{-0.35}$				
$\mu_{t\bar{t}}$	0.99 ± 0.03	ϵ_c	0.35 ± 0.02	0.34 ± 0.02	$0.33^{+0.02}_{-0.01}$
$\mu_{t\bar{t}+c}$	$1.60^{+0.64}_{-0.60}$	f_{cb} (10^{-3})	25 ± 6	26 ± 3	26 ± 2
$\mu_{t\bar{t}+b}$	$1.45^{+0.54}_{-0.34}$				

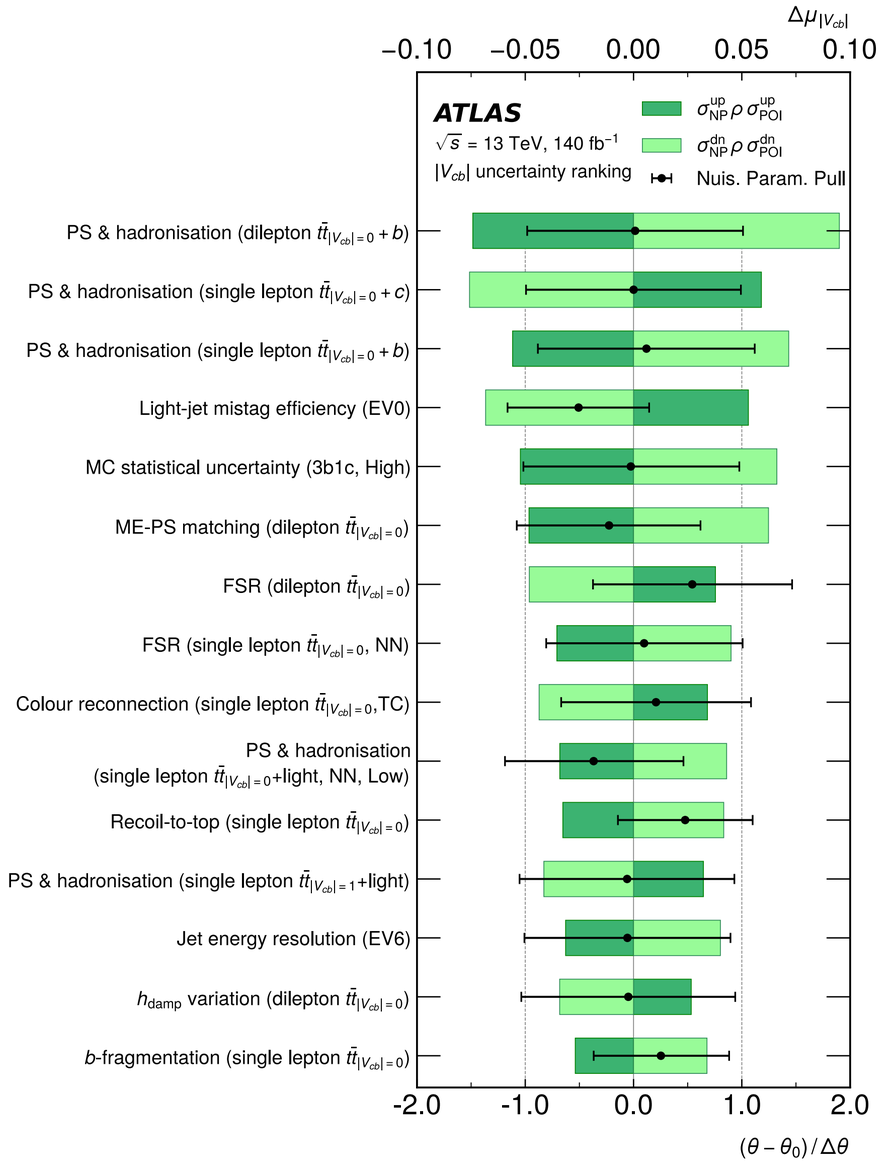
Post-fit values of all free parameters of the fit

Uncertainty	Up/Down [10^{-3}]
Modelling of $t\bar{t}$	8/9
↪ PS and hadronisation	5/6
↪ Others	5/6
Jet flavour tagging calibration	2.9/3.1
↪ Light-jet	2.5/2.8
↪ b-jet	1.2/1.3
Simulation statistics	2.6/2.7
Jet calibration	2.4
Modelling of non-$t\bar{t}$ processes	1.6
Others	0.8
Systematic uncertainty	9/10
Statistical uncertainty	7/9
Total uncertainty	11/14

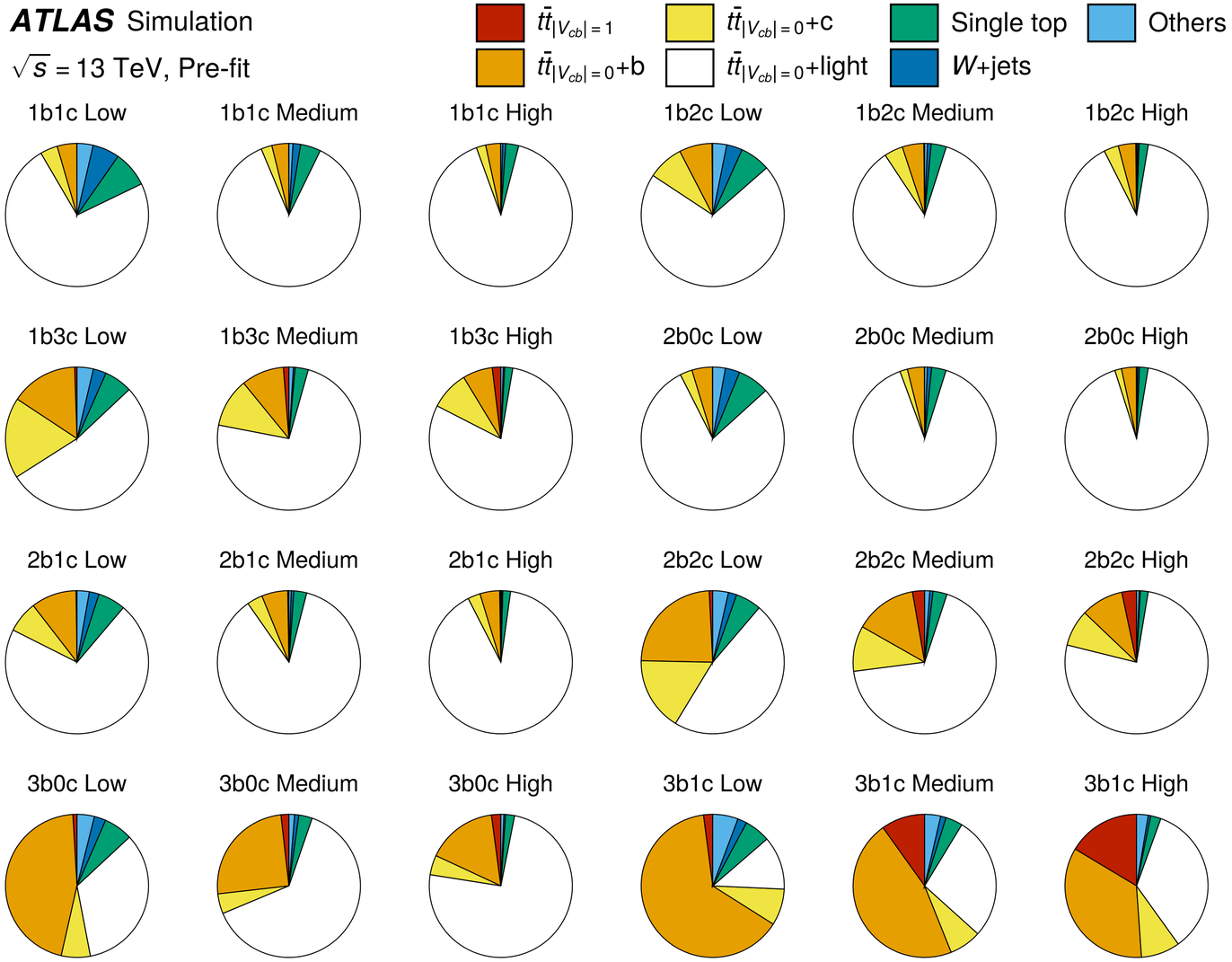
Uncertainty breakdown in $|V_{cb}|$

Ranking of the largest systematic uncertainties

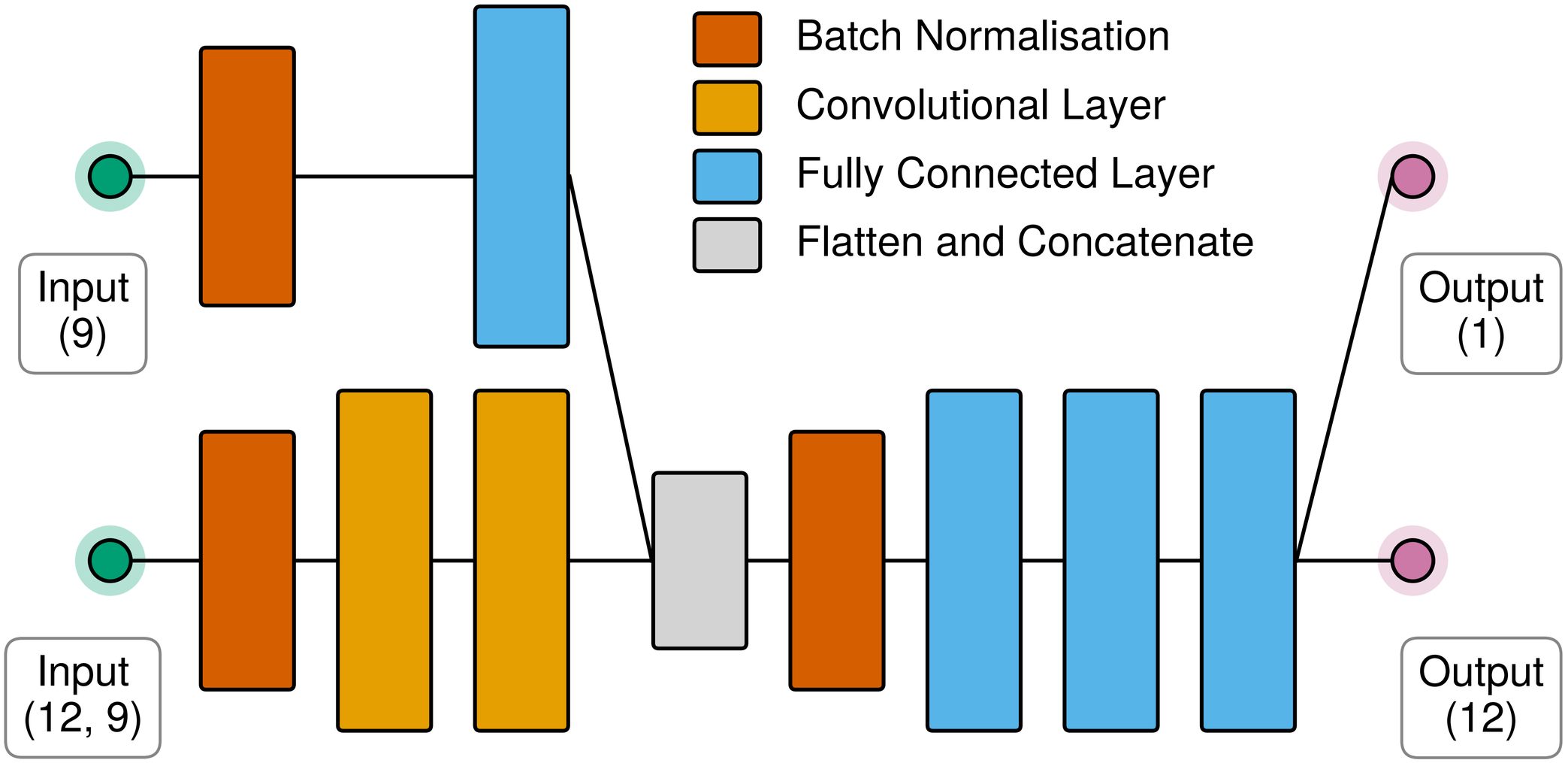
- Ranking of the impact in the $|V_{cb}|$ uncertainty for the systematic uncertainties, using the covariance method



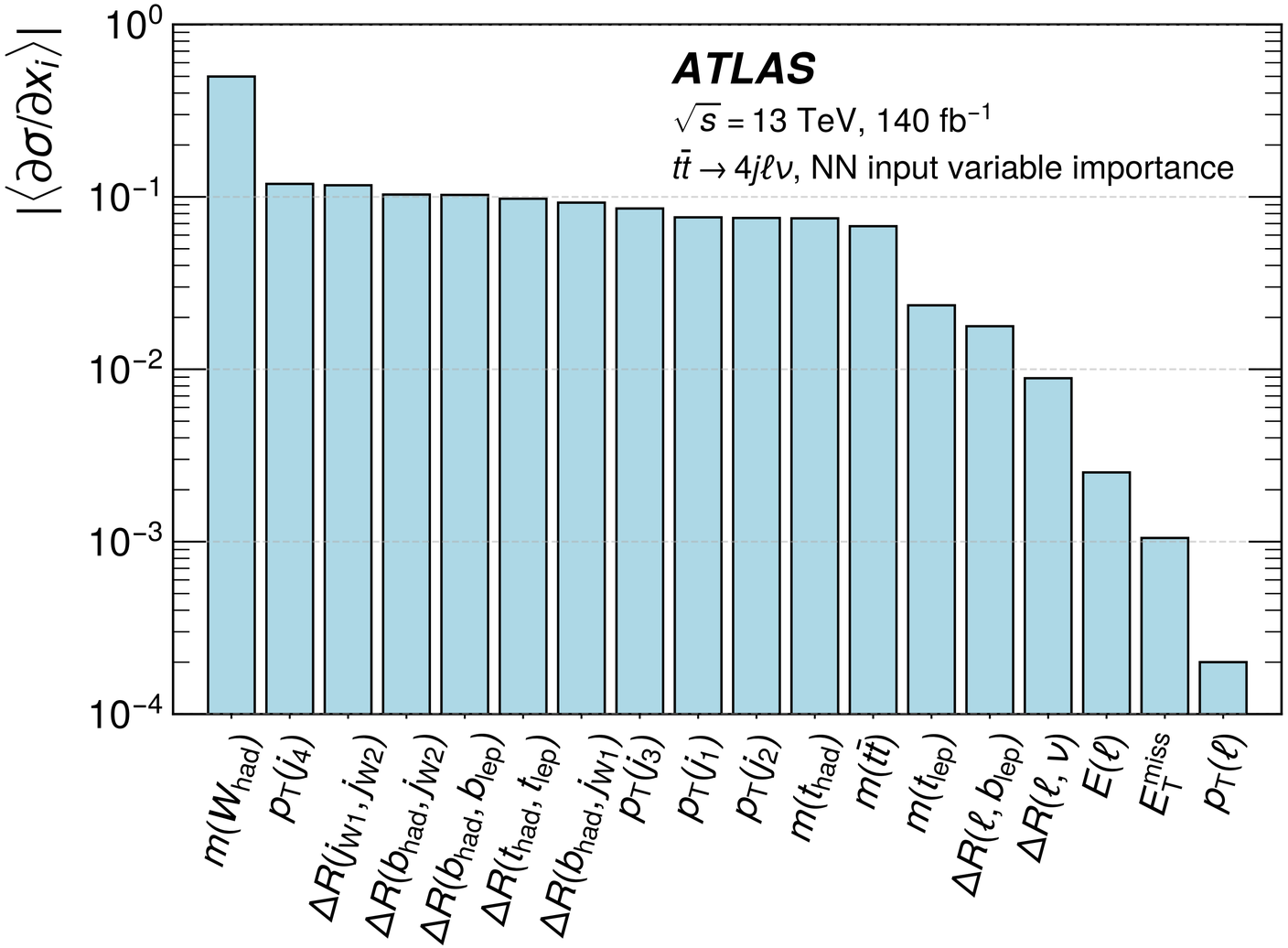
Pie charts over pre-fit yield in all analysis regions



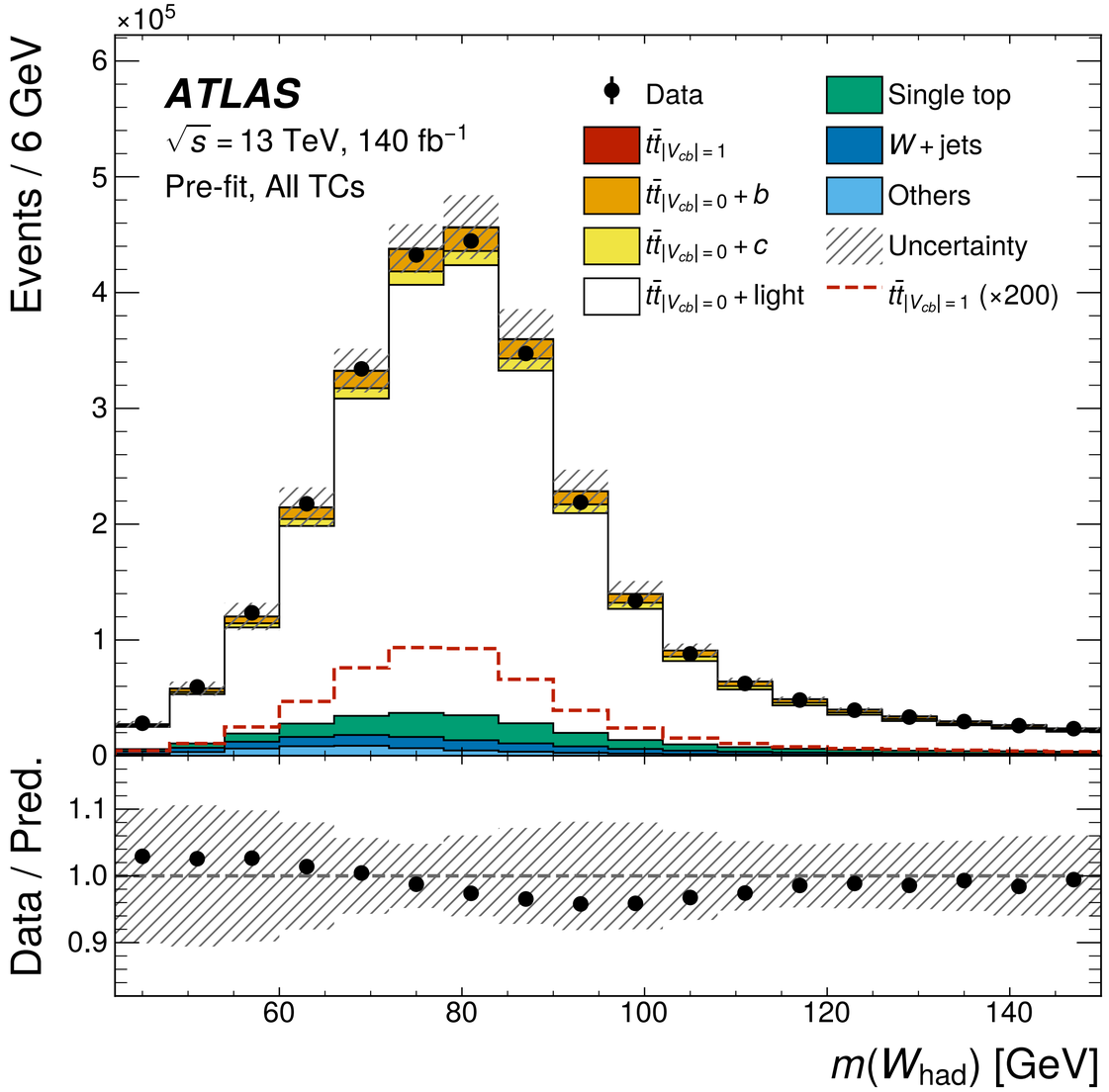
NN architecture

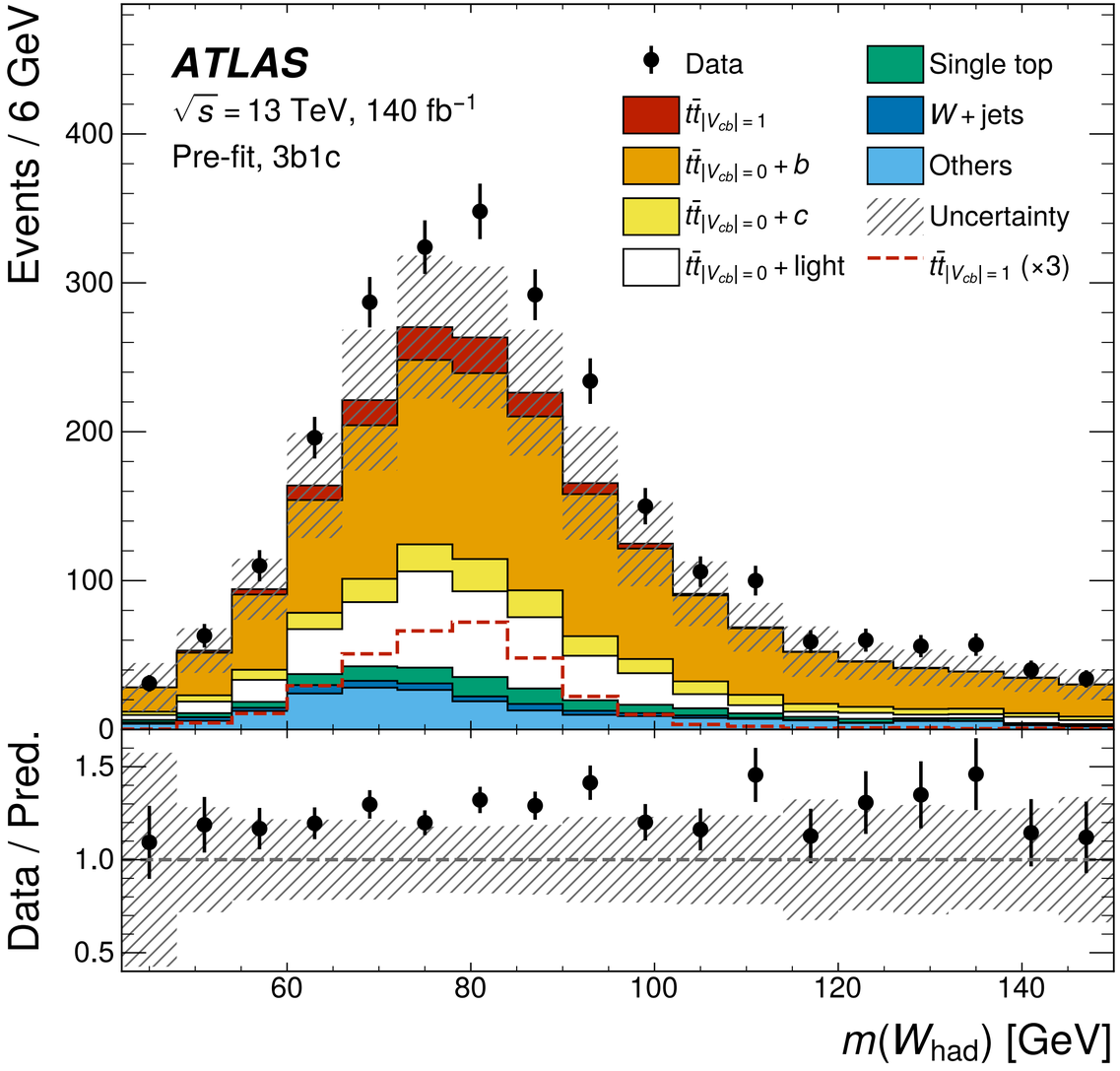


NN input ranking



Hadronic W boson mass plots





In-situ charm jet calibration

- Charm jet efficiency ε_c and $c \to b$ mis-tag rate f_{cb} calibrated in two steps

$(\varepsilon_x \equiv f_{xx})$

- First, in MC, best fit tagging parameters found by minimising χ^2:

$$\chi^2 = \sum_j \left(\frac{N_j - N \cdot p_j(T)}{\Delta N_j} \right)^2, \quad T = \begin{pmatrix} \varepsilon_l & f_{lc} & f_{lb} \\ f_{cl} & \varepsilon_c & f_{cb} \\ f_{bl} & f_{bc} & \varepsilon_b \end{pmatrix}$$

Uses central calibration

Calibrated in-situ

Rows sum to 1 $\Longrightarrow$ 6 free parameters

N_j: Number of events in region j, ΔN_j is the uncertainty

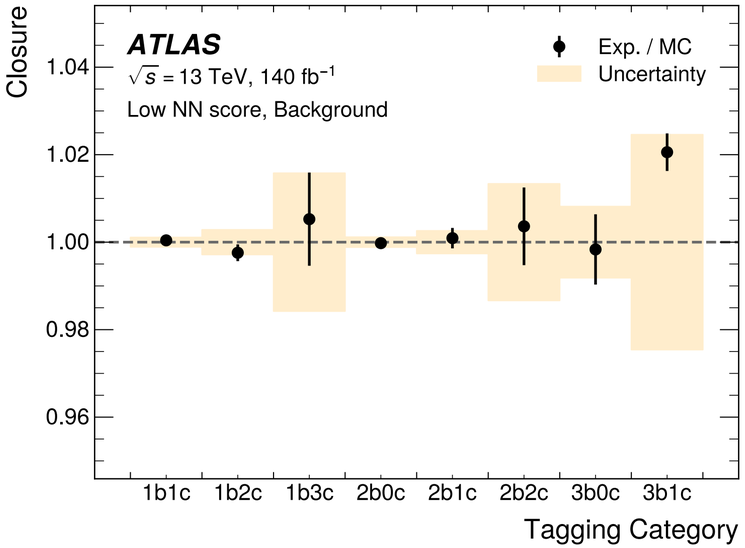
N: Total number of events

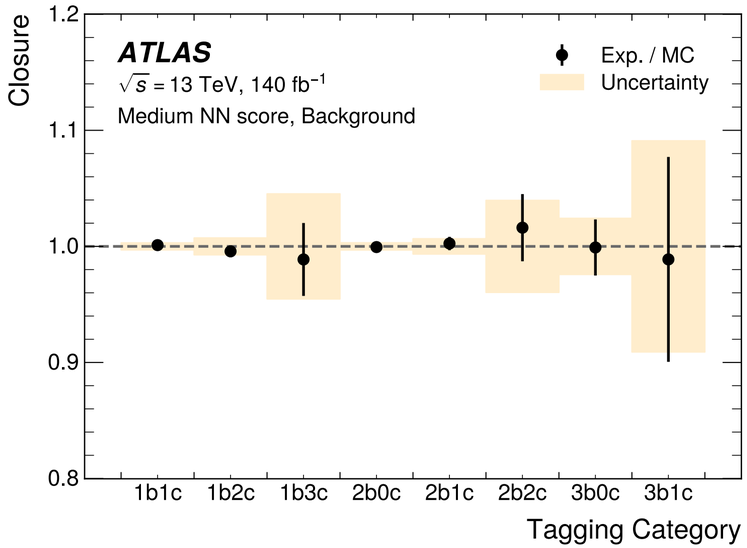
$p_j(T)$: Probability of an event ending up in region j given T and the true jet flavours of the event

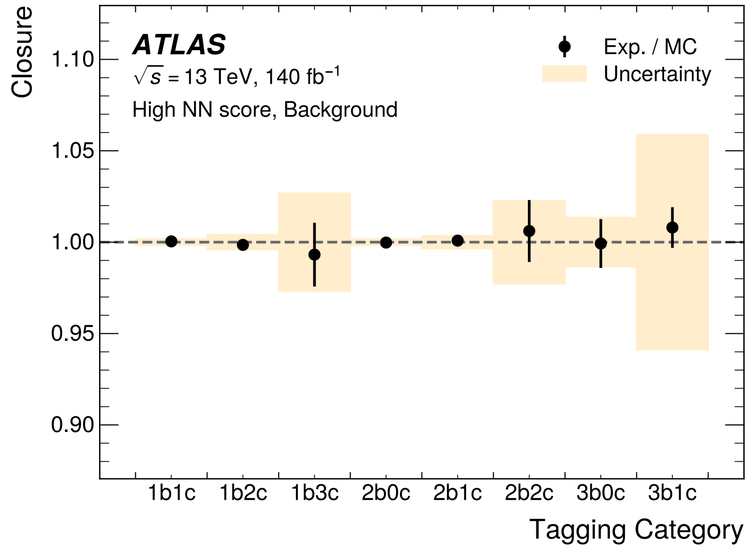
- Kinematic efficiency dependence $\Longrightarrow$ efficiency fit separately in the Low, Medium and High NN regions

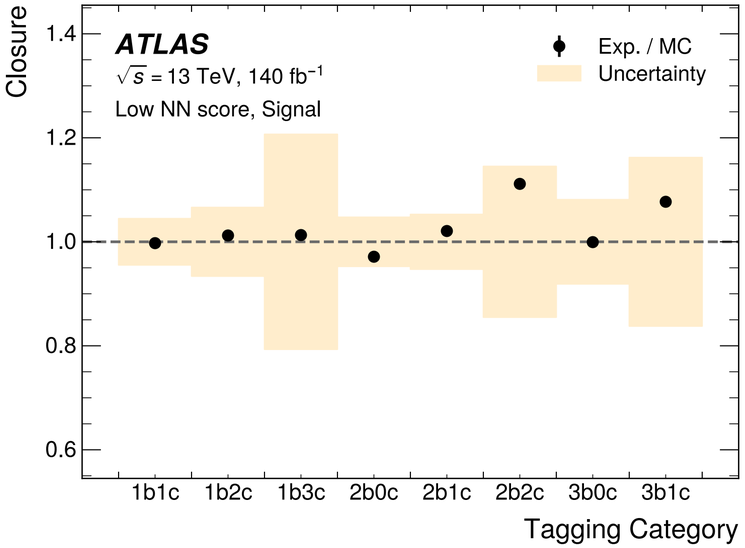
- Best fit parameters fixed, except for ε_c and f_{cb}, which are free floating in the fit to data

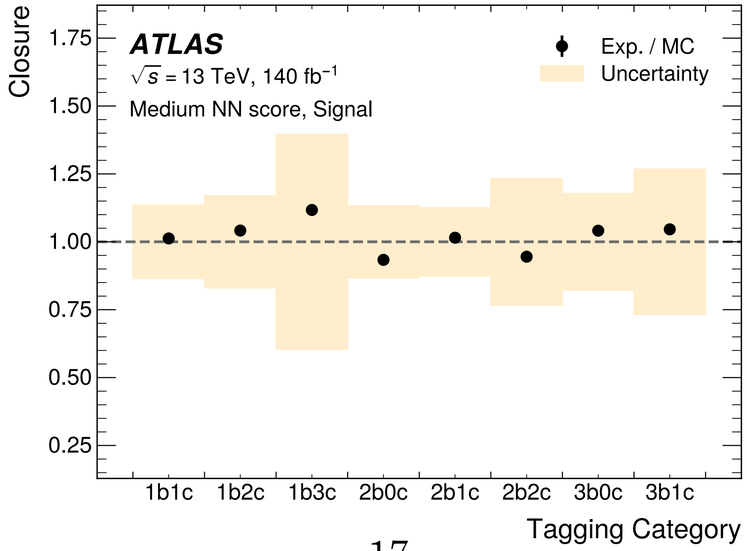
Charm-tagging closure plots (all within statistical uncertainty)

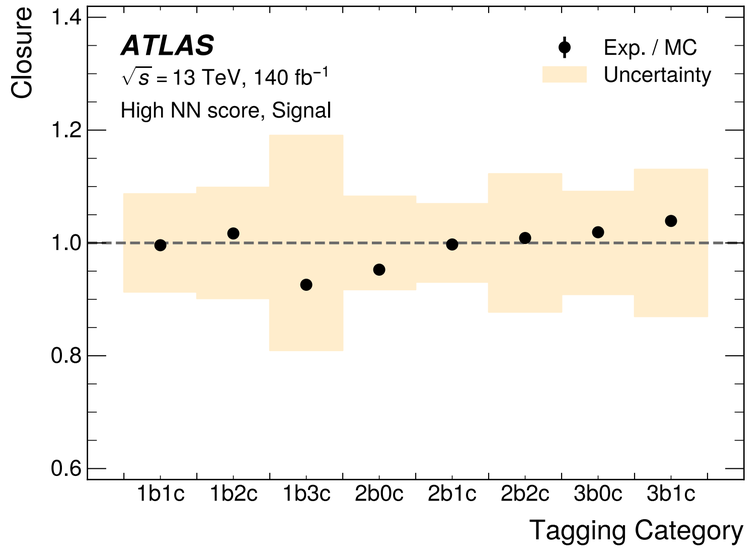
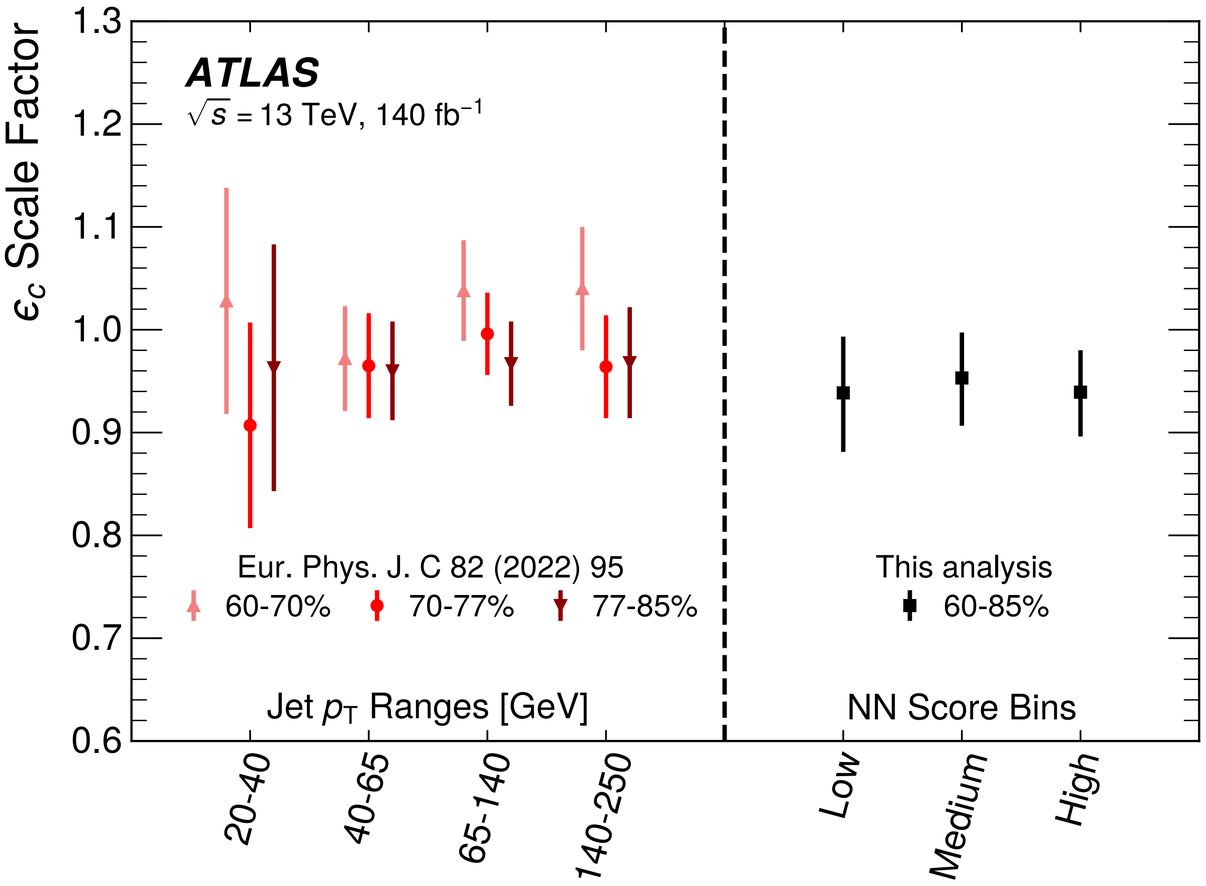
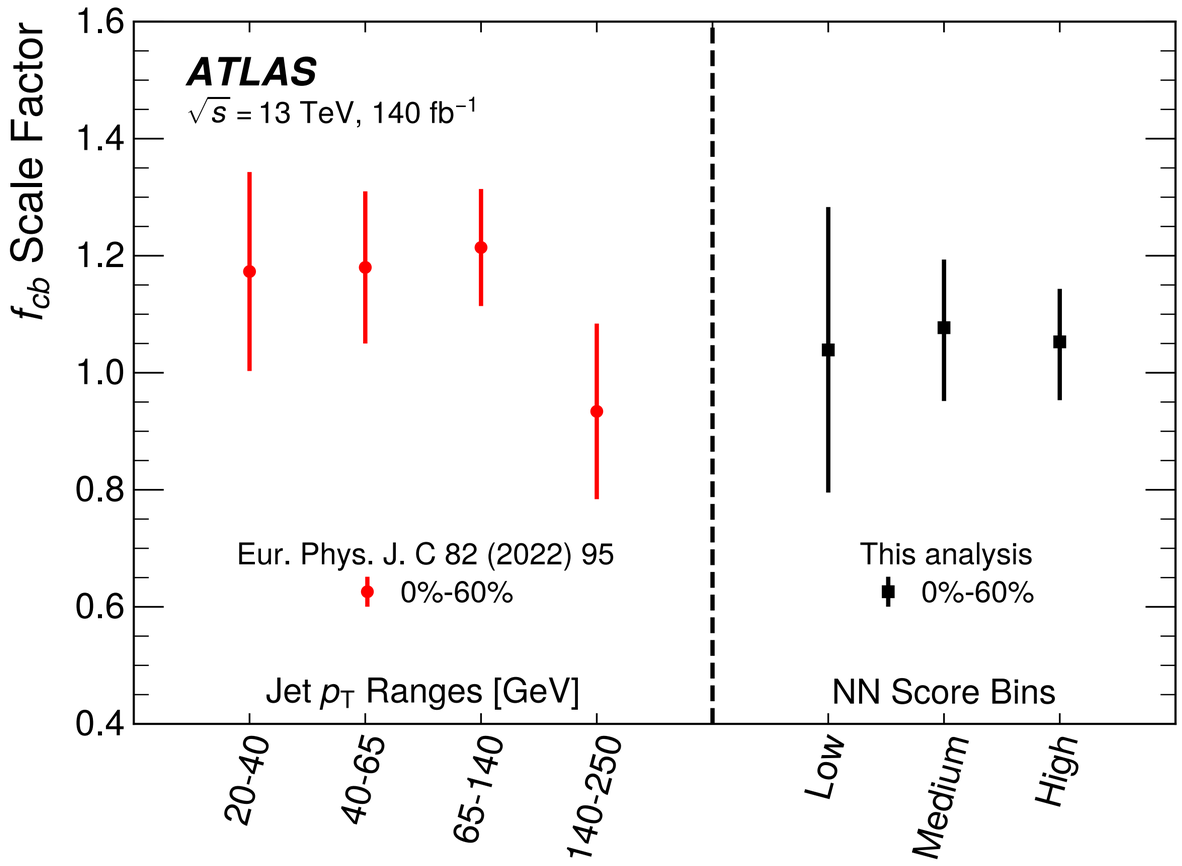












Charm jet efficiency and mistag rate scale factors